CHAPTER 5

Selection of Materials

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CHAPTER 5

Selection of Materials

Introduction

1 Before any structural design work is commenced it is necessary to give consideration to the selection of materials for each part of the structure. While steel may be the obvious choice for the majority of the structural components, there may be local constraints which point to the use of other materials in particular areas, for example using aluminium or composites to save top-weight; moreover there may be requirements on the whole hull, such as for mine countermeasures vessels where a low magnetic signature is of overriding importance, which lead to a structure entirely in non-ferrous materials.

2 Even where steel is chosen it must not be forgotten that there are many different types of steel, each of which has its own characteristics which may be appropriate for a particular application. The cheapest and most readily available mild steel, for example, has no specified toughness and is unlikely to be suitable for external hull structure potentially subject to impact loading in cold conditions; at the other end of the spectrum there are the high strength quenched and tempered steels which have very high resistance to cracking but which are relatively difficult to weld and are mainly used for submarine hulls.

3 This chapter, therefore, will discuss the advantages, disadvantages and potential applications of structural materials and will present typical mechanical properties with references to more detailed data. The discussion starts naturally with ferrous materials, moving from there to other metals and finally through wood to modern composite materials.

Ferrous Materials

4 *Table 5.1* illustrates the principal properties of the more generally used steels. BS4360 is the standard for structural steels, but equivalents from Lloyd's Register and Ministry of Defence specifications are given. In the case of the Naval Engineering Standards it is usual to call up the relevant BS grade of steel from within the standard and to define options where the BS leaves the user with choices, for example for rolling tolerances.

5 Mild steel is the most commonly used and cheapest shipbuilding material. However, as mentioned above, it has a particular disadvantage that no toughness (crack arresting property) is specified. It has been shown by Sumpter et al (1989) that for practical engineering structures there is no thickness of mild steel below which brittle properties may not be found. Consequently it is

dangerous to use mild steel in any large structure which may be subject to relatively high rates of loading (for example collision or minor weapon impact) in cold conditions. In extreme conditions even high sea states may be enough to trigger a brittle failure as described by Corlett et al (1987). In ships of any size it is desirable to use either a steel with a guaranteed toughness, such as BS4360 Grade 43D or to use some form of crack arrestor. This may be either a rivetted seam or a strake of much tougher steel; in the latter case Grade 50EE would probably be necessary to absorb the energy of a running crack. At least four of these crack arrestors would be needed around the girth, for example at the deck edge or shear strake and at the turn of bilge.

TABLE 5.1
Properties of Steel Plate

	Steel Type					
Property	Mild Steel	Notch Tough MS	B Quality (crack arrest steel)	Q1(N) (HY80)	Q2(N) (HY100)	HSLA80
Approximate Equivalent Specification	NES791 Part 1 BS4360 43A Lloyd's Grade A	NES791 Part 2 BS4360 43D Lloyd's Grade D	NES791 Part 3 BS4360 50EE Lloyd's Grade EH32	NES736 Part 1	NES826 Part 1	MIL-S-24645 (SH)
Yield Strength (MPa)	245 (⩾63 mm) to 275 (⩽16 mm)	245 (⩾63 mm) to 280 (⩽16 mm)	280 (⩾32 mm) to 310 (⩽22 mm)	550-655 (0.2% proof)	690-790 (0.2% proof)	550-690 (0.2% proof)
Tensile Strength (MPa)	430-510	430-540	450-590	≮1.4 × proof	≮1.11 × proof	-
Limit of Proportionality (MPa)	216-263	216-263	263-355	480-585	-	-
Young's Modulus (GPa)	201-208.5	201-208.5	199-207	197-207	197-207	207
Poisson's Ratio	0.3	0.3	0.3	0.3	0.3	0.3
Charpy Temperature/ Energy (°C/J)	-/-	-10/27	-30/40	-84/70-100	-	-84/35
Elongation (%)	22	22	20	20	20	20
Cost (£/Tonne) (1987 prices)	252	274	289	1550	-	-

6 Some higher strength steels are also shown in *Table 5.1*. Of interest are the quenched and tempered high yield steels used mainly in submarines to provide a deep diving capability while keeping hull weight to a minimum. **Quenched and Tempered** steels, Q1(N) and HY80, have been in use for many years but their higher strength successors have not yet been cleared for general use. Problems lie mainly in the difficulties of welding the material reliably under shipyard conditions as it requires very careful control of pre-heat and post-weld cooling. **High Strength Low Alloy** (HSLA) steel, for example MIL-S-24645 (1984), is growing in popularity as both a warship material as well as for use in very large merchant ships. It can have strength similar to or more than HY80 but is cheaper and easier to weld; its use in ship construction is discussed in some detail by Montemarano et al (1986).

7 High strength steels are usually advocated in surface ships as a means of saving weight. However, it must be remembered that it is only the strength and not the stiffness of the material which is greater, and that in a conventional ship structure overall strength is governed at least as much by buckling as by yield failure. Consequently, it will never be possible to save weight in a structure in proportion to increased yield strength of the material. Moreover, fatigue crack initiation and, to a lesser extent, propagation are usually controlled by weld properties and these do not necessarily improve with those of the parent material. High strength steels are always more costly than conventional structural steels and so a choice between them must take proper account of the apparent advantages being limited by the other factors mentioned above. Having said that, however, it may be possible to reduce the vulnerability of a structure to weapon attack by making use of the greater energy absorption capabilities of high strength steels, and this aspect will be discussed in more detail in Chapter 15.

TABLE 5.2
Advantages and Disadvantages of Steel

Advantages	*Disadvantages*
Normally ductile	Corrodes readily
Virtually isotropic	Has no lower fatigue limit (but see Chapter 13)
Easily formed and fabricated	Heavy
Plentiful	Brittle at low temperatures
Easily alloyed or heat treated for special properties	(Magnetic)
Easily repaired	

8 Advantages and disadvantages of steel in the marine environment are shown in *Table 5.2*. The advantages need no elaboration and serve to illustrate why steel remains the most popular material for ship structures. The disadvantages, however, must not be forgotten, in particular the ease with which steel corrodes in a wet environment leading to heavy expenditure on protective measures, and the fact that a welded steel structure has no lower fatigue limit. All ship structures which are subject to cyclic loading will exhibit fatigue failure at some point in their lives and the only solution then is to cut out the damaged material and replace it with new. See Chapter 13 for a discussion of fatigue and means of minimising fatigue damage.

9 **Stainless steel**, usually of the 316 (austenitic) type, can be used in structural applications and, because of its stable oxide film, is resistant to corrosion. It is also non-magnetic and as such has potential applications in mine countermeasures vessel structures. However, the chloride content of seawater attacks the oxide film and if there is a shortage of free oxygen, for example in stagnant areas, then the oxide film cannot reform and severe crevice corrosion occurs. Recent developments include high molybdenum austenitic steel and relatively high nitrogen duplex steel, both of which may offer significantly improved resistance to crevice attack. Although these materials may be used in pipe systems they have not yet been proposed for structural applications. Generally, in any case, the use of stainless steel in quantity cannot be justified unless its advantages outweigh its high cost, and unless the shipbuilding industry is geared to its use and fabrication procedures.

10 Welding is now universally used to assemble a steel structure, but care still needs to be taken to ensure adequate quality control, especially when welding in the open. Comprehensive non-destructive examination of surface ship structures is not common practice, and incidents abound of significant weld defects being found when a vessel is in service. Fortunately steel, provided that it has adequate ductility for the expected working temperatures, is a very forgiving material and the results are rarely catastrophic, *but* ships have been lost due to failures that are too rapid for an emergency message to be sent out, and so the cause of failure can only be conjectured. Where non-destructive examination is applied, radiography is the usual method for light structure and simple butt joints. Ultrasonics are also commonly used for more complex connections such as tee butts. Particular areas of the hull which should be given special attention are the berth butts and most importantly around the margin, sheer and garboard strakes, butt welds in the keel, and positions where welds cross each other. If longitudinal stiffener butts are not staggered away from the plate butts then the connections in these areas should also be examined.

11 In designing steel structures, allowance must be made for loss of thickness during rolling and later due to corrosion. It is conventional practice to use the bottom of the manufacturer's thickness tolerance band for structural calculations, thereby taking the worst case. However, with the increasing use of probabilistic methods of design (see Chapter 11) it is likely that the mean and standard deviation of thickness will be used in the future, so allowing a less conservative, more optimised structure.

12 With modern methods of preservation, corrosion *should* not be a problem for new designs. However, it is prudent to make some allowance in the hull and in wet spaces such as tanks and bilges, and unless better data are available a mean thickness reduction of 0.5 mm (in addition to the rolling tolerance) is recommended in these areas. The basis for this figure is that corrosion in ship's steel structure is usually in the form of local, relatively deep, pitting where the protective system has broken down. A few pits have little effect on overall strength, but they become more significant as they increase in number, and an average loss of strength equivalent to 0.5 mm thickness is reasonable. In one area only, that of the flat keel, is a greater allowance recommended. The flat keel is always in contact with the dock blocks when the rest of the hull is being painted, and although a different position should used on each occasion of docking, a corrosion allowance of about 2 mm is recommended as a precaution against poor preservation, again in addition to the rolling tolerance.

TABLE 5.3
Properties of Some Non-Ferrous Metals

	Metal			
Property	Aluminium 5083/0	Titanium (Commercially Pure)	Copper-Nickel 90/10 (CN102)	Copper-Nickel 70/30 (CN107)
Specification	BS1470	DTD5023 (3-71) or BS 2TA2	BS2875	BS2875
Density (g/c^3)	2.70	4.51	8.94	8.94
0.2% Proof Stress (MPa)	125	290	100	120
Tensile Strength (MPa)	275-350	390-540	280	310
Young's Modulus (GPa)	70	100	132	152
Elongation (%)	16	22	36	27
Cost (£/Tonne) (1987 prices)	2000	10,000	2000	2000

13 **Aluminium** is by far the most popular structural material after steel, and its properties are compared with other non-ferrous metals in *Table 5.3*, and comparison with steel can be taken from *Table 5.1*. The most commonly used structural alloy is 5083 from BS1470 in the 'O' (annealed) condition. From its density and strength it is easy to see that in a simple structure without cyclic load a weight saving of the order of 65% can be made compared with steel. However, the disadvantages as well as the advantages of aluminium are shown in *Table 5.4*, and in addition to the cost (approximately £2000/tonne for plate at 1987 prices) it will be seen that the principal difficulty is that of fatigue life; fatigue design limits are defined in BS8118 (which replaces BS CP118). In fact, in a cyclically loaded structure such as a ship it can be shown that to achieve acceptable fatigue life the stresses in the aluminium have to be kept so low as to almost completely negate the apparently advantageous strength to weight ratio.

TABLE 5.4
Advantages and Disadvantages of Aluminium

Advantages	*Disadvantages*
Lightweight	Poor fatigue properties
Does not corrode easily	Low melting point
Easily formed	Fairly expensive
Easily fabricated	Strength and stiffness less than steel
Readily available	
Normally ductile	
(Non-magnetic)	

14 For a new design if, for example, stability is a problem, it will almost always be cheaper to increase the beam by a small amount that to reduce top-weight by fitting an aluminium superstructure. However, when an old ship has to be modified, the use of aluminium may then be justified, but then the question of fire needs special consideration. Aluminium will only burn at very high temperatures which would rarely, if ever, be reached in a ship fire. However, it begins to lose its strength at about 200°C and melts at about 650°C so it is clearly undesirable to use it in areas where fire is a consideration. It is possible to insulate aluminium to meet Department of Transport rules for fire retardant and load bearing structure, but UK naval policy is never to use it for primary structure or for ladders and walkways. Where small structures such as isolated deckhouses are built of aluminium for fitting onto steel structure the methods of connection for RN vessels are specified in NES155 Part 1 and welding procedures in NES768.

15 Having said that, aluminium is frequently used for the hulls of small vessels where light weight is more important than cost, maintenance problems or fire risk, for example for coastal patrol boats. A number of UK boat and shipbuilders have produced vessels either all or part in aluminium, but mostly for export. Minesweepers have also been built of aluminium, but the problem of eddy currents induced as the ship passes through the earth's magnetic field leads to the need for degaussing, and so its non-magnetic properties are only of marginal advantage. In the case of the TON Class MCMVs built during the 1950s in wood with aluminium framing, while the ships have been extremely long lived with a significant number still in service in the late 1980s, the cost of maintenance has been high with a large contribution due to corrosion of the aluminium frames (hydrolysed aluminium oxide - HAO) which, amongst other things, expands the structure and pushes off the wood planking.

TABLE 5.5
Advantages and Disadvantages of Titanium

Advantages	*Disadvantages*
High strength to weight ratio	Very expensive
Good fatigue properties	Not easy to fabricate
High melting point	May corrode quickly
Low thermal conductivity	Not readily available in large quantities

16 **Titanium** and its alloys offer some attractions for marine use. As well as good mechanical properties and light weight (see *Table 5.3*) it has good resistance to corrosion and impingement attack (provided that the oxygen content is low) and it is non-magnetic. Because of its high strength to weight ratio it has been used in the Former Soviet Union for the hulls of deep diving submarines, but so far it has found no structural use in surface ships, mainly on account of its cost (about £10,000/tonne at 1987 prices). Its advantages and disadvantages are listed in *Table 5.5* and a source reference is Donachie (1982).

17 For practical purposes it is commercially pure (CP) titanium to DTD5023C (1971) or BS 2TA2 which is most likely to be used structurally, as in addition to being durable in the marine environment it is relatively easy to weld in shipyard conditions. It has been considered as a candidate material for MCMVs alongside stainless steel and glass reinforced plastic (GRP), but on top of its high cost the problem of eddy currents rules it out in the same way as for aluminium. Its only current semi-structural use is for MVMC engine exhaust systems where its resistance to high temperatures is an advantage over both aluminium and GRP, and for the bolts used to strengthen the attachment of frames to hull in the HUNT Class MCM vessels.

18 As a hull material it would be very susceptible to fouling, and galvanic corrosion problems would arise if it was attached to any other structural metal in a wet environment. However, there would be no significant problems with welding (usually TIG or MIG processes are used) and conventional methods of NDE are effective.

19 In the mid 1970s there was much enthusiasm around the world for **copper-nickel** as a hull material, for example see Manzolillo et al (1976) and the papers from the Cupro-Nickel Alloys for Anti-Fouling Symposium at RINA (1980). Advantages and disadvantages of the material are listed in Table 5.6 but the most notable ones are the fact that it can be welded to steel, and its resistance to corrosion and fouling leading to significant fuel saving, with no reduction of effectiveness with time due to leaching out. However, the mechanism of its fouling resistance requires it to be bare and unpainted, while the influence of the antifouling properties does not extend beyond the immediate surface. It is of interest that Manzolillo et al (1976) report significant fouling of painted draught marks on an otherwise clean hull.

TABLE 5.6
Advantages and Disadvantages of Copper-Nickel

Advantages	*Disadvantages*
Resists fouling	Expensive
Easily fabricated	Cannot be painted if resistance to fouling is required
Easily formed	Noble with respect to all other structural materials
Can be welded to steel	Fairly low strength
Good fatigue properties	Heavy
Resists corrosion	

20 The type of copper-nickel that appears to be the most economical to use for structures is 90-10 Cu-Ni from BS2875, although 70-30 has been used and is recommended for welding consumables, but for welding to steel a 65-30-5 Ni-Cu-Fe composition is recommended. Standard MIG or TIG processes may be used. Mechanical properties of 90-10 and 70-30 Cu-Ni are given in Table 5.3 and more information can be found from West (1982).

21 For economy an arrangement consisting of Cu-Ni plate or Cu-Ni clad steel plate on steel frames is likely to be best because Cu-Ni structural sections are not available. This would have the disadvantage of risking more rapid corrosion of the steel due to galvanic action between the two metals in wet spaces. However, little corrosion has been reported from the few vessels at sea, and it seems that a good paint scheme and regular visual inspection should suffice.

22 On the limited evidence available it seems that copper-nickel reacts in much the same way as steel to the normal rigours of a ship's life, that is general wear and tear. It does appear, however, to be much more resistant to fatigue damage than steel (Manzolillo et al (1976)) although no rigorous tests are reported on it as a structural material.

Wood

23 Wood is probably the oldest material used for shipbuilding, but now, except for some small boats and yachts, has generally gone out of favour. The reasons for this lie mainly in the cost of large quantities of large sections of timber, and in the relative difficulty of assembling complex structures which require much skill and time. There is indeed a scarcity of skilled labour for woodworking in shipyards as well as a shortage of suitable timber in much of the world.

24 Wood is a natural polymer based on the cellulose chain and has properties which are strongly orientated; only 50-60% of the material is cellulose, the remainder being lignin which contributes little to the strength. In consequence wood is strong in tension and compression in the direction of the grain, but relatively weak in other directions. Physical and mechanical properties of timber may be found in a number of publications, for example Findlay (1975) or Desch (1988), but are critically dependent on moisture content. Generally, for ships' hulls, the properties for the highest moisture content should be used, and a table of typical dry and wet properties for a number of different timbers is given by Chalmers (1988(c)). Because of the variability of wood it is advisable to leave a large factor of safety, perhaps of the order of five, on quoted strength figures.

25 These days it is usual to find African hardwoods most easily available, see Farmer (1972), often laminated into plywoods. Plywood has its grain orientated in alternate piles at 90° to each other, so it can be made quite strong in plane stress conditions and may be treated as orthotropic although in reality it is anisotropic. However, it is difficult to build into complex structures as almost all joints will involve either shear loading or loading through the thickness, directions in which the material is weak. Such structures tend to get very bulky and will also have poor resistance to impact loads. Additionally, use of wood screws will have to be avoided as they pull out easily under impact or shock loading. For details of the properties of marine plywoods see BS1088.

Fibre Reinforced Plastics

26 There are many composite materials used in engineering but for shipbuilding, and especially for hull construction, fibre reinforced plastic (FRP) is the most common material and the only one which is likely to see significant use in the foreseeable future. This section will concentrate of glass reinforcement as being the most common and certainly the cheapest, but other types of reinforcement will be introduced where appropriate. In discussing FRP it is necessary first to describe the resins and fibre reinforcements separately as their properties significantly affect the finished product. However, for design purposes the laminate properties are of greatest importance and these will be covered at some length. Because the properties of composite materials, unlike metals, can be tailored to meet a very wide range of requirements, it is necessary for the designer to understand their composition before considering their use in design.

27 The means by which FRP carries load is principally through the fibres, which are much stiffer than the matrix material (the resin). However, on their own the fibres would only be capable of supporting tension, and even then it would be difficult to apply the load. The purpose of the resin is, therefore, to support the fibres under compression and shear and to transfer the load into them. Consequently the shear properties of the resin and of the bond between the resin and the fibres are of especial importance, and one particular line of weakness in a laminate is shear between laminae (so-called interlaminar shear strength), across which the fibres do not penetrate unless special weaving techniques are used.

28 The **resins** of greatest application in reinforced plastics, and used exclusively in warships to date, are of the unsaturated polyester type. The main attractions of polyester resins are low cost, room temperature cure capability and reasonable resistance to water absorption. The other most frequently used resins are the epoxy types. These can be tailored to have a variety of mechanical properties with good heat and chemical resistance but are more expensive than polyesters. To achieve optimum performance, which will generally be better mechanically than that of polyester, they usually require heating during the curing process although cold cure epoxies are becoming available for structural applications. Epoxy resins are more resistant to osmosis and surface blistering than are polyester resins, but osmosis is only likely to occur in polyesters if a surface gel-coat (a glossy unreinforced layer of resin) is used.

29 Other resins in commercial use include vinylesters, phenolics, acrylics and furanes, all of which may be used in areas where special properties or resistance to particular chemicals are required. Phenolic resins in particular appear to have a bright future due to their excellent performance in fire, although their mechanical properties currently cannot match those of polyester. The resistance of phenolics to the marine environment is not yet known but their use in load bearing structures is discussed by Forsdyke et al (1983). For further details of available resins and properties see the report of ISSC Committee V.8 (1988).

30 All the above resins are thermosetting compounds and, except for epoxy, require the addition of a catalyst to promote the chemical reaction which achieves cure: the catalyst does not become part of the cured resin system. Epoxy resins consist of a 'resin' and 'hardener' which are mixed and cure together to form the final cross-linked product. An accelerator can be added to control the working and setting times of the resin, and a thixotropic agent can be incorporated to slow or stop the resin running down when applied to vertical surfaces. Polyester resins can be fully cured at room temperature, a property which is essential for the construction of large assemblies such as hulls. Currently isophthalic polyester resin is specified for warship construction as it has better resistance to water absorption than the more commonly used orthophthalic resins. The specification for resin, catalyst and hardener for warship construction is NES167.

31 Some thermoplastic resins are also now becoming available in quantity, for example polyetherimide (PEI) and polyetheretherketone (PEEK). They are potentially attractive because of their good higher temperature stability and because it is possible to conceive them being weldable, but they are at present extremely expensive. Uses to date are almost exclusively small moulded radomes and other fittings on aircraft.

32 In the UK the majority of **glass fibre** in use today is 'E' glass, which is a low alkali borosilicate glass. 'S' glass, known in the USA as 'R' glass, is somewhat stronger but is also more expensive. It has not yet seen any significant use in the marine field. Deficiencies in laminate properties stem, in any case, more from the glass finish and weave and from the resin type used.

33 The majority of glass fibre used in warship construction is in the form of woven roving, that is a weave of continuous, parallel laid, untwisted bunches of fibres. The weave can be balanced, with the same quantity of glass in both the warp (fibres in the direction of weaving) and the weft (transverse fibres), or may have a preponderance of glass in either direction to vary its directional properties. Ultimately there is 'unidirectional' cloth which has only sufficient glass in one direction to hold the weave together. In warship design to date only balanced weaves and unidirectionals have been used, but biassed weaves have been tried experimentally in a corrugated hull as described by Smith (1986) and Gass et al (1986).

34 Also used sparingly in warships but frequently elsewhere and especially in boat construction is chopped-strand-mat (CSM) to BS3496. This is a mat of short (~50 mm) lengths of fibre randomly distributed and lightly bonded to provide stability during handling. It has relatively poor mechanical properties but is cheaper than woven cloth and has easier handling and resin wet-out characteristics (the ability of the resin to soak through and thoroughly 'wet' the glass fibres). However, long lengths will not support their own weight and so it is difficult to use CSM in mechanical dispensers. CSM is used extensively in low stressed applications such as small boats and life raft covers, and is also useful in large structures to build up thickness, for example at connections where a generous radius is wanted but stresses may be fairly low.

35 For mass production chopped glass can be sprayed directly into the mould coincidentally with the spraying of the resin. This has the advantage of very rapid production, but the mechanical properties are generally lower than with hand laid-up CSM as the resin proportion tends to be higher. A further problem is that thickness is very difficult to control and so the process is only suitable for manufacture of low quality parts.

36 Other materials are available in proprietary form, such as a sandwich of CSM between layers of woven roving, which can be used as a compromise for quicker build up of thickness without too great a sacrifice of strength. As well as glass, aramid fibres (KEVLAR) or carbon fibres may be used either on their own or in conjunction with glass, and using such a lay-up a laminate can be designed to have optimum performance for a particular application. Stiffness and strength can be improved but at significantly greater cost per unit weight, and the designer has to balance the cost against the reduced weight to see if use of these stronger materials is justified. *Table 5.7*, derived from Harris (1986), gives the properties of commonly used fibres including some not yet used in marine construction. Further information on the use of 'advanced' fibres, and comparisons with steel and aluminium structures, are presented by Marchant and Pinzelli (1987).

TABLE 5.7
Properties of Reinforcing Fibres

Material	Property Density (g/cm^3)	Fibre Diameter (mm)	Young's Modulus (GPa)	Tensile Strength (GPa)
Carbon HM	1.8	7 - 10	400	2.0 - 2.8
Carbon A	1.9	7 - 10	220	3.2
Boron	2.6	130	400	3.4
E-Glass	2.5	10	70	1.5 - 2.0
S-Glass	2.6	10	90	4.6
KEVLAR 49	1.45	12	130	3.6
Polyethylene	0.97	12	117	2.6

37 Fibres in either CSM or woven form can be supplied pre-impregnated with resin under pressure and part cured. It is especially useful for small components of relatively complex shape where the 'pre-preg' can be formed into the mould reasonably cleanly. Fibre to resin ratio can be high as excess resin is removed during the initial manufacturing process, but cure has to be completed by heating and so it is not feasible for use in large items.

TABLE 5.8
Physical Properties of Typical Laminates

	Properties of Common Composites					
Laminate	Cloth Weight (kg/m^2)	Resin Content (by weight) (%)	Recommended Tolerance (%)	Composite Density (tonne/m^2)	Composite Thickness/ Laminate (mm)	Thickness Tolerance (mm)
Woven Roving	0.78	50	±2	1.62	0.96	±0.020
CSM	0.61	70	±5	1.45	1.42	±0.070
CSM	0.30	70	±5	1.45	0.70	±0.035
Unidirectional	0.64	50	±2	1.62	0.79	±0.015

38 For structural applications a mix by weight of 50% glass to 50% resin has been aimed at in the past for woven rovings, although with modern automated production it is possible to get to 60% glass or more. As the glass density is 2.5 tonne/m^3 and the resin density about 1.2 tonne/m^3, the density of a 50/50 composite will be 1.62 tonne/m^3. With CSM the resin ratio is higher and the density proportionately less. Some physical properties of typical laminates are given in *Table 5.8* and using simple proportions it is possible to calculate equivalent properties for other laminates.

39 In discussing properties of FRP it must be remembered that it is a manufactured composite material and, at least as used in ship construction, is generally laid-up by hand. Consequently, there is a considerable scatter in mechanical test results and for design purposes it is prudent to use minimum properties which may be significantly less than the mean. Properties of typical laminates are given in *Table 5.9* and are the mean less two standard deviations which are recommended for design. Properties of other laminates may be estimated using a method of mixtures as described, for example, by Harris (1986).

TABLE 5.9
Mechanical Properties of Typical Laminates

	Woven Roving		Unidirectional		CSM
			Warp	Weft	
Glass Content (%)	50 ± 2		54 ± 2		30 ± 2
UTS (MPa)	207		345	34.5	96.5
UCS (MPa)	172		345	96.5	117
In Plane Shear Strength (MPa)	62.1		62.1	-	62.1
Interlaminar Shear Strength (MPa)	13.8		13.8	13.8	13.8
Shear Modulus (GPa)	3.09		3.34	3.34	3.45
	Warp	Weft			
Young's Modulus (GPa)	14.7	13.1	24.5	7.77	6.89
Poisson's Ratio	0.12	0.14	0.08	0.25	0.13

40 The influence of fibre content on laminate properties is significant and it is important to specify clearly the intended content when designing in composites. Furthermore, a variation in the resin to fibre ratio will be accompanied by a difference in thickness for a given number of laminates; a higher fibre content produces a stronger but thinner laminate but frequently the gain in specific properties does not compensate for the loss of thickness especially when buckling is a critical failure mode. It is therefore most important in critical areas to quote minimum thickness as well as the number of plies. For a polyester and glass composite using a glass density of 2.5 tonne/m^3 and a resin density of 1.2 tonne/m^3 the thickness per laminate for a particular glass/resin ratio can readily be calculated.

41 It will be obvious from *Table 5.9* that the material is anisotropic. However, it is acceptable in the early design stages to assume isotropy for woven roving or chopped strand mat using the properties given, but in the later analysis as details are developed it is essential to take account of the variation of properties with direction, although an assumption of orthotropic properties is often acceptable. *Figure 5.1* shows how strength and modulus vary with direction in a laminate of 780 g/m^2 woven roving and further data may be found in Harris (1986) and Smith (1972).

42 In *Table 5.9* it will be noted that interlaminar shear strength is very low. This is a measure of the strength of the resin alone and it is important to be aware of interlaminar weakness when designing details. It is very difficult to reinforce a laminate through the thickness as it is made, and if through-the-thickness loads are likely to be significant then some form of mechanical clamping such as bolting is recommended.

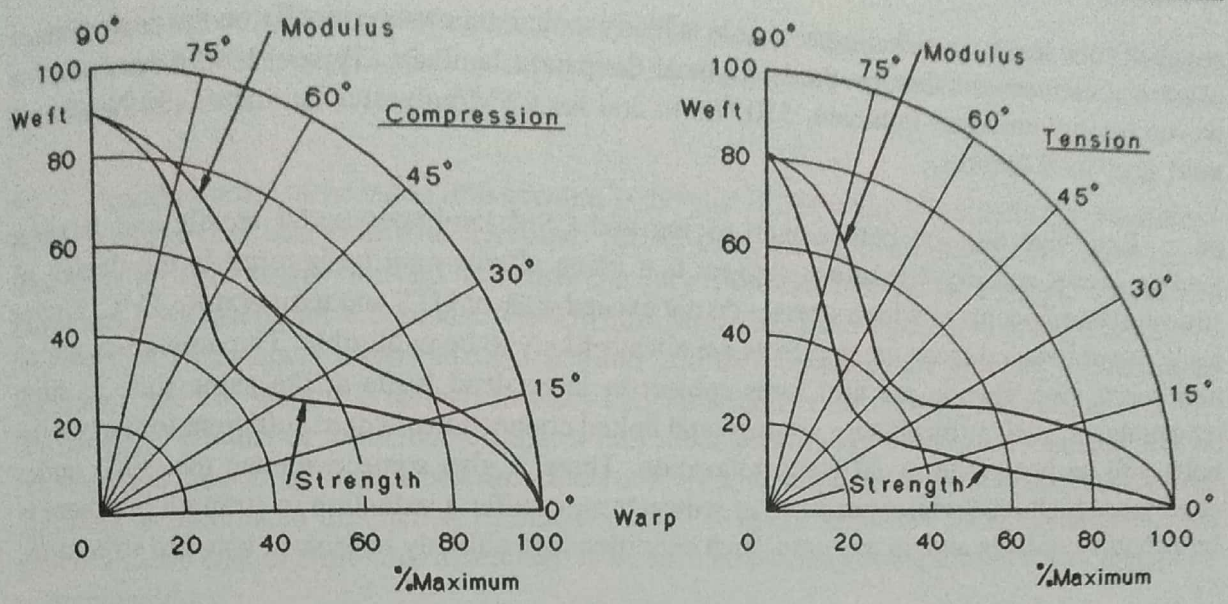


Figure 5.1 Directional Properties of 780gm Woven Roving in Polyester Resin Laminate

43 The interlaminar strength problem is made worse if one face has cured before the second face is laid up. Such a bond is called a secondary bond and even with good abrasion of the cured face it can never be totally reliable. Secondary bonds occur frequently in construction of stiffeners and seatings when hull and other structure will have cured long before these parts are laid up; care must then be taken to ensure that adequate strength is available to withstand any shock or impact loading which may be applied.

44 Tests on woven roving reinforced polyester specimens indicate a fatigue limit of about 25% of UTS (see also paragraph 52 and Chapter 13), with a further reduction if the material is immersed in water. Fatigue induced resin cracking and fibre debonding may lead to water absorption and significant loss of strength and stiffness. However, while fatigue failure must be considered in design it is unlikely that tensile stresses will be high enough in the parent laminate to cause concern and fatigue in structural connections is much more likely to be a problem. Results of tests carried out on connections are listed by Dixon et al (1972) and Beale (1971), but there is as yet little useful data in the marine field. For references to fatigue in aerospace laminates, which provide interesting background but are not directly relevant to marine structures, see the report of ISSC Committee V.8 (1988).

45 Because of their relatively high strength and low elastic modulus, FRP laminates may, under ideal conditions, be able to absorb elastically up to 10 or 15 times as much impact energy as equivalent steel or aluminium plates. However, in practice, with low interlaminar tensile and shear strength, lack of ductility and weakness at secondary bonds, fabricated FRP structures are likely to have less overall impact strength than equivalent metal structures in which large amounts of energy can be absorbed by plastic deformation. Under impact loads normal to its surface a FRP laminate will usually fail by interlaminar shear and by delamination caused by transient through-thickness tensile stresses. A comparative measure of impact strength may be obtained by standard Charpy, Izod or drop-weight tests as described by Beale (1971). As for fatigue, the strength of a complex FRP structure under impact loads is likely to depend more critically on the performance of bonded connections than on the strength of the parent laminate. Typical Izod values are, for woven roving/ polyester laminate, 530 Nm/m and for CSM/polyester laminate, 430 Nm/m (cf mild steel 1600 Nm/m).

46 Extensive tests on both woven roving and CSM laminates under tensile and flexural loading in wet and dry conditions suggest that creep effects may be ignored in the design of structural components in which stresses do not exceed 40% of UTS and temperature 15°C. Under cyclic wave induced loads creep effects are always likely to be negligible. The only areas which may merit investigation are structures subject to large dead loads at the same time as high temperatures, such as machinery seatings and bolted connections, where sufficient torque on the bolts will be needed to avoid creep relaxation. There is also some evidence that FRP under *continuous* high load while immersed in seawater may suffer a reduction in strength but there is little detail available and, in any case, such conditions are unlikely to arise in warship structures.

47 For further details of the derivation of properties for different combinations of fibres and matrix materials see Harris (1986), McCrum (1971) and Jones (1975).

Use of Fibre Reinforced Plastics

48 Having discussed the properties of FRP and seen some of its disadvantages it is appropriate to ask why should it be used at all, as FRP is clearly not a convenient material for the design and manufacture of large complex structures. Its advantages over steel and other metals lie in its lack of magnetic properties and electrical conductivity, its resistance to corrosion, its relative sonar transparency and good strength to weight ratio and, in some applications, its low stiffness and good fatigue properties. Its advantages over wood lie in its resistance to rot and to marine organisms, and in its availability. Its disadvantages stem mainly from:

a. Lack of secondary bond strength.

b. Poor interlaminar strength.

c. Low stiffness in most applications.

d. Cost and labour intensive production.

It follows that the use of FRP must always be justified against more conventional materials and an example of such a justification for the SANDOWN Class mine countermeasures vessels is presented by Chalmers et al (1984).

49 Consequently, for structures where the advantages are not relevant or the disadvantages are severe, metal remains the better material. For warships the use of FRP can be justified for the structure of mine countermeasures vessels (for its non-magnetic properties), small vessels where repeatability and simplicity apply, for deckhouses where low stiffness can be used to advantage (see Chapter 8) and where ease of maintenance can be balanced against cost (Smith and Chalmers (1987)), and for components such as submarine castings where resistance to corrosion and low weight are utilised.

50 Another point to be taken into account is the cost of FRP which is significant. In addition to the material cost being three to five times that of steel, the production process is very labour intensive. At 1987 prices finished hull costs can vary from £3000/tonne for a simple commercial hull to £15,000/tonne for a complex warship structure. This latter figure includes the detail of a warship hull with many bulkheads and seatings and the complications inherent in high shock resistance and low weight. It follows that any FRP structure should be kept as simple as possible; furthermore, it must be remembered that a hull mould and many other lesser moulds will be required and the cost of these is best amortised over a number of units. Labour costs are, however, reducing as automated production techniques are developed: These are most advanced for flat panels and the cost of structures assembled from such panels may be significantly less than those quoted above.

Failure Criteria for FRP

51 For design purposes it is necessary to adopt a failure criterion which allows for the presence of biaxial and shear stresses at any point in the structure because of the essential anisotropic nature of FRP. One such criterion, corresponding to a generalisation for orthotropic materials of the Von Mises isotropic yield criterion and due to Azzi-Tsai (1965) is:

$$\sigma_x^2/X^2 - \sigma_x\sigma_y/X^2 + \sigma_y^2/Y^2 + \tau_{xy}^2/T^2 = 1 \qquad (5.1)$$

where σ_x, σ_y and τ_{xy} are in-plane direct and shear stress, and X, Y and T are corresponding direct and shear strength. For further discussion of failure criteria see McCrum (1971), Raghava (1989) and Chalmers (1993). In a plane stress situation where one stress is much greater than the other, equation 5.1 is rather optimistic and a safer one would be:

$$|\sigma_x|/X + |\sigma_y|/Y + |\tau_{xy}|/T = \alpha \qquad (5.2)$$

where α lies between 0.15 and 0.2.

52 Factors of safety associated with failure criteria must be related to specific applications, but it is worth noting that Gibbs and Cox (1960) recommend the following minimum factors for the ratio of ultimate strength to working load:

Static short term loads	2
Static long term loads	4
Slowly varying loads	4
Fatigue and repetitive loads	6
Impact loads	10

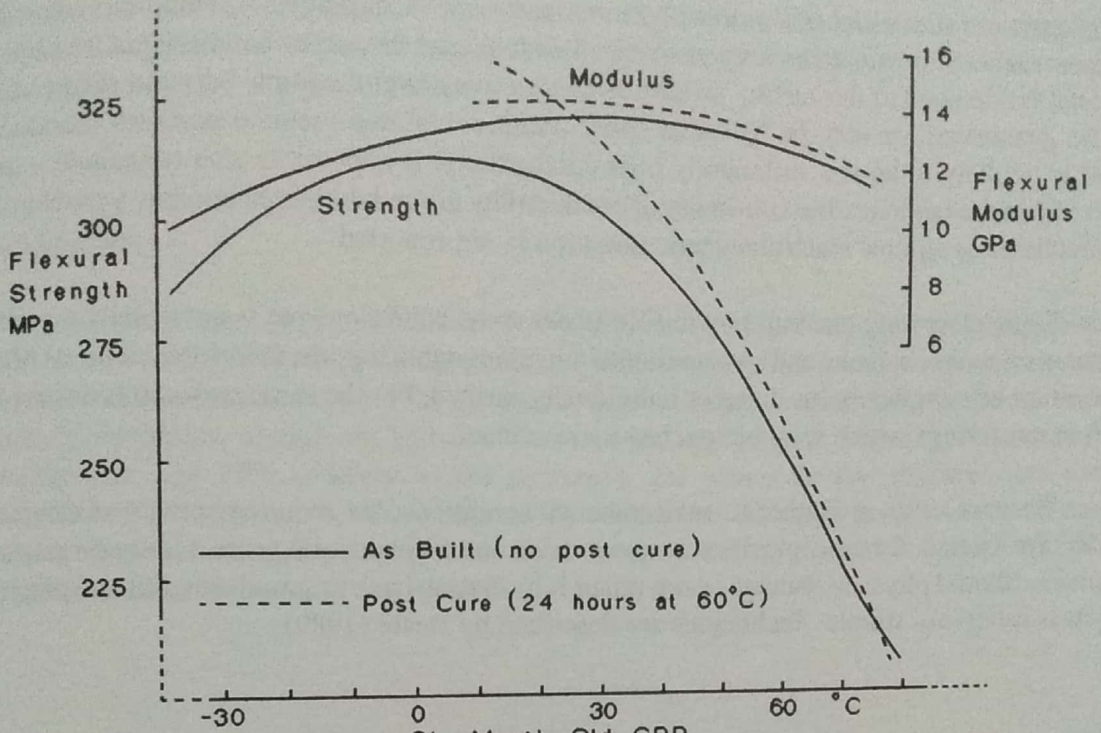
Resistance of FRP to the Environment

53 The commonly used resins in FRP will tend to soften at temperatures of around 80°C and strength and stiffness begin to deteriorate quite fast above 40°C although as thermal conductivity is very low, surface temperature can rise well above this level before there is danger of significant reduction of strength within the laminate; *Figure 5.2* illustrates the effect of temperature on modulus and strength for isophthalic polyester resin. Some modern thermoplastic resins, and indeed phenolic resins, have better temperature properties but have not yet been validated for use in the marine environment. The coefficient of thermal expansion of a glass woven roving laminate is close to that of steel and so *strains* induced by changes in sea and air temperatures will be similar to those in a steel ship of the same size. However, because of the low Young's modulus of FRP the temperature induced *stresses* will be very low and a temperature gradient of as much as 40°C would be unlikely to cause a stress greater than 5.5 MPa.

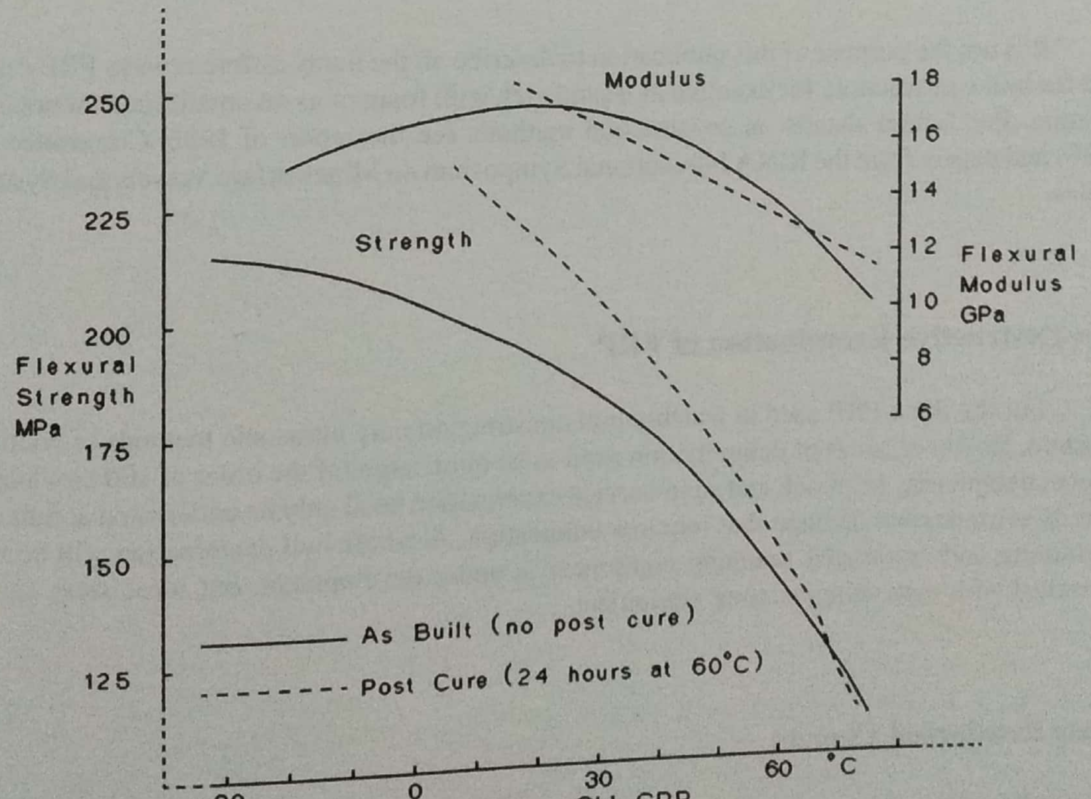
54 Polyester and epoxy FRPs are also resistant to most commonly used liquids. Tests have been carried out against almost all liquids that are likely to be carried on a ship and the only substances that have been shown to have an effect are certain disinfectants, strong acids and alkalis, polystyrene cement and any solvent containing trichloroethylene or methylene chloride. This latter material has a particularly severe effect and, as it is used in some paint removers, extra vigilance is needed to keep it away from FRP structures. To provide increased resistance to the environment for warship hulls a special isophthalic polyester resin was developed to provide better resistance to water absorption than the more commonly used orthophthalic resins. The effect of water absorption on mechanical properties of polyester resins is discussed by Dixon et al (1972). However, where contact with water is continuous, for example on the underwater hull and in tanks, it is recommended that the strengths and stiffnesses listed in *Table 5.9* are reduced by 15%. It is also important that all laminate surfaces are intact and that any cut edges are sealed with resin before they come into contact with water.

55 Resistance to fire of good quality FRP is, contrary to commonly held belief, very good. A wide variety of tests have been undertaken on glass woven roving and CSM reinforced polyester showing that, depending on the thickness of the laminate, it is quite possible to withstand high temperature fuel fires for 60 minutes or more. Unfortunately, the results of these tests have not been published openly, but Chalmers et al (1984) describe an incident on a vessel at sea where a fire burned in the engine room for around four hours; the damage was restricted to that compartment and repairs to the structure took only five weeks. To assist inspection after a fire it has been shown by Dodds (1987) that in the case of polyester, if the resin is not discoloured then the mechanical properties have not been unacceptably degraded. In fire, however, polyester and epoxy resins evolve large quantities of dense black smoke which makes fire fighting difficult, although the smoke is not toxic unless fire retardants have been added to the resin. Phenolic resins do not evolve any significant smoke and offer a great improvement over conventional resins but their mechanical properties and especially their durability in the marine environment are not yet proved.

56 FRP laminates are relatively transparent to electromagnetic transmissions at a wide range of frequencies and, while this can be an advantage in minimising some radar reflections (depending on what is behind the FRP) it causes problems with security and integrity of emissions



Six Month Old GRP



Three Year Old GRP

Figure 5.2 Effect of Temperature on Flexural Properties of GRP

from communications and other electronics compartments. Consequently, compartments where emissions must be protected have to be screened with an earthed conductive film. Such a film may be metal foil bonded to the surface so long as conductivity over the joints between sheets of film can be guaranteed, or may be by metal spray: Paint containing metallic particles (conductive paint) is unlikely to have a sufficiently high conductivity. It is possible also to include a metal mesh within the laminate, but continuity of conductivity around the edges remains a problem and its effectiveness against electromagnetic radiation is not reported.

57 Static electricity can build up in FRP under some conditions but is not usually a problem except in oil tanks. In tanks and systems containing flammable liquids, therefore, all metal fittings must either be completely insulated or individually earthed. For the same reason it is desirable to earth metal fittings which may be touched by personnel.

58 Because of its resistance to environmental conditions, the requirements for maintenance of FRP are limited, for example there is no corrosion and paint coverings are mainly for cosmetic purposes. Should physical damage occur, repair is by cutting back to sound material and patching, which is relatively simple. Techniques are described by Beale (1989).

Hull Construction in FRP

59 It is not the purpose of this publication to describe all the many different ways FRP can be used for hull construction, for example as a sandwich with foam or as an unstiffened monocoque structure. For further details on construction methods see the report of ISSC Committee V.8 (1988) and papers from the RINA International Symposium on Minewarfare Vessels and Systems (1984).

Non-Destructive Examination of FRP

60 For the thick FRP used in warship hull construction only ultrasonic methods of NDE are effective. However, areas of delamination need to be quite large (of the order of 100 mm length) before strength may be at risk and so in-service examination need only be undertaken at refit or if there is some known damage that requires delineation. A whole hull examination will be time consuming and automated scanning equipment is under development, but local areas can be examined with ease using existing equipment.

Glass Reinforced Cement

61 Glass may also be used as a reinforcement in a matrix of cement, known as GRC, which is sprayed into a shaped mould. The glass is in short lengths and is a special alkali resistant type. GRC is very resistant to fire and is used for architectural mouldings and service trunks in buildings, but its long term resistance to seawater has not been investigated. Its density is high (about 2.6 tonne/m^3) but one small boat is known to have been built in GRC and there may be a future as the material is relatively cheap.

Conclusions

62 This chapter has given a brief overview of all current and potentially useful ship structural materials. Clearly steel and, in the main, mild steel provided that toughness requirements are satisfied, will continue to be used for the vast majority of marine structures for the foreseeable future. Nevertheless, aluminium and FRP have limited applications where their properties are advantageous, and FRP is likely to see increasing use where its low stiffness and ease of maintenance are of positive value, such as in deckhouses. Copper-nickel, which is easy to fabricate and no more expensive than aluminium, could also have a future where low maintenance effort is a strong requirement.